Comparision of Traditional and Novel DTI Acquisition Schemes for the Human Spinal Cord

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Introduction: The spinal cord (SC) extends from the foramen magnum to the second lumbar vertebrae. Like the brain, the SC is composed of both grey matter (GM) and white matter (WM), but the WM is on the periphery of the SC. WM is often the target for quantitative imaging methods such as Diffusion Tensor Imaging (DTI), which faces challenges in the SC. First, the SC is small and since the WM is proximal to CSF, motion and partial volume effects can be detrimental. Additionally, for DTI, fast imaging methods such as single shot (SSH) echo planar imaging (EPI) can cause severe distortion making robust estimations of tract-specific DTI indices difficult. However, DTI indices such as fractional anisotropy, radial, and parallel diffusivity have been marked as possible indicators of tract integrity, myelination and axonal damage (1), and thus have obvious clinical applications. Lastly, since the SC is somatotopically organized and hypothesized to be the root of much of the neurological disability in diseases such as MS, the ability to probe individual tracts in the spinal cord with measures sensitive to pathology becomes critical. There are, however, technical hindrances when examining the human SC *in vivo*. The SC is mobile (cardiac pulsations during normal sinus rhythm); the B0 field is inhomogeneous (due to the presence of large vertebral bodies), which causes artifacts when using EPI. Our hypothesis is that by introducing cardiac triggering as well as a novel 2D-navigator for multi-shot EPI, we can provide DTI information in the cervical SC with greater robustness.

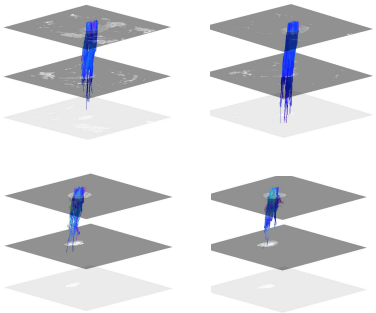

Fig 1: Fiber Tracking for each acquisition method (From Top Left: SSH w/o gating, SSH w/ gating. MSH w/o gating, MSH w/ gating)

Methods: MRI Acquisition and reconstruction: DTI were obtained in 4 healthy volunteers on a 3T Philips Achieva using a 2 channel MultiTX body coil (transmission), and a 16 channel neurovascular coil (reception). SSH DTI acquisition strategies had been previously developed (2) and were implemented. Diffusion-weighted dual spin-echo multi-shot (MSH) EPI sequence utilizing SENSE and a 2D navigator was developed. Both single-shot (SSH) and MSH acquisitions were performed with and without cardiac gating using peripheral pulse oximeter. Imaging parameters were: FOV/acq.resol./slice thickness, 100x100mm 1.19×1.19-1.37mm^2/5 mm; TE/TR/α/NSA, 56-81ms/3 RR intervals/90º/3-5 averages; SENSE =2; *b*-value=500 s/mm^2; gradient orientations, 6 (MSH) and 15 (SSH) and 12 slices. Total scan time was approximately 7 minutes depending on heart rate. Multi-shot reconstruction was performed using an *image* space sampling function with simultaneous correction for motion-induced shot-to-shot linear and non-linear phase variations using a 2D navigator (3), whereas SSH image reconstruction was performed on the scanner using conventional SENSE reconstruction method. All offline image reconstruction and post-processing were performed using Matlab.

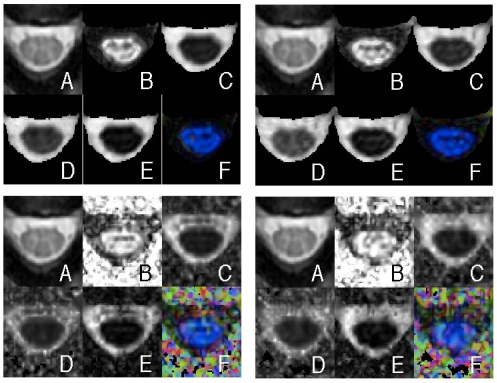

Fig 2: DTI and anatomicals for each of the acquisition methods (From Top Left: SSH w/o gating, SSH w/ gating, MSH w/o gating, MSH w/ gating). (A) smFFE Anatomical Image (B) FA (C) MD (D) $\lambda_{\parallel}$ (E) $\lambda_{\perp}$ (F) Color Map

Data Analysis: The diffusion tensor was estimated voxel-wise and DTI metrics were calculated using the eigenvectors (principle eigenvector, PEV) and eigenvalues of the diagonalized diffusion tensor: fractional anisotropy (FA), mean diffusivity (MD), parallel diffusivity ($\lambda_{\parallel}$), and perpendicular diffusivity ($\lambda_{\perp}$). Additionally, the diffusion color map was calculated from the FA and PEV. In order to characterize the impact of the acquisition strategy alone in a small cohort, we chose to analyze the DTI-derived indices over the entire cord (rather than segmenting WM and GM), or looking segmentally, after cord selection, the perimeter of the cord ROIs were eroded by 2 voxels to minimize partial volume effects. All slices for each DTI-derived index were collected for each acquisition method (SSH without gating, SSH with gating, MSH without gating, MSH with gating) and the mean (±SD) was calculated. To provide an estimate of the acquisition method on the robustness of the PEV, a 3D tractography was performed in DTIStudio (5), with seed ROI placed at the most superior slice. These fibers were then colored according to the direction of the PEV at each voxel (Red – RL, Green – AP, Blue – SI).

Results and Discussion: Visual inspection of the fiber tracking (Fig. 1) shows the accumulated errors in the PEV as the tracking moves away from its seed ROI. SSH fibers show more robustness than the MSH fibers, where fibers fail to reach beyond 5 slices (25mm) with one seed ROI in most instances. However, the SSH tractograms show that gating results in significant improvement in fiber stability over the non-gated case. Not only is the extent impacted, but also the orientation: SSH cardiac gated fibers remain blue (SI direction) over the cord length, yet in the MSH case, and potentially due to uncorrected thru-plane motion from the 2D navigator the PEV shows significant deviation from SI direction. Additionally as we obtained the data over the same scan time, the MSH case had only 6 diffusion directions, which we know from the literature can create errors in the accuracy of the PEV (4). We hypothesize that greater diffusion orientations and potentially a 3D navigation technique could be utilized in this case due to the magnitude of the rostral caudal motion of the SC. Fig. 2 shows the individual DTI maps. Two things are of note: comparison between MSH and SSH shows clearly reduced distortion in the MSH case compared to the SSH, yet there is an observable change in the magnitude of the noise for all MSH cases. Lastly, mean ± SD of the individual DTI indices are given in Table 1. From the table alone, it is difficult to assess the accuracy of the individual techniques. However, all methods provide DTI-derived indices congruent with the literature range. Further analyses will assess the reproducibility, and the impact of SNR on the individual indices. We suspect that in an equal SNR regime, a navigated MSH DTI approach will be superior to SSH in artifact mitigation and robustness of the derived indices.

	FA	MD (μm/ms)	$\lambda_{\parallel}$ (μm/ms)	$\lambda_{\perp}$(μm/ms)
SSH(w/o gating)	0.60 ± 0.13	1.0 ± 0.20	1.8 ± 0.31	0.62 ± 0.21
SSH(w/ gating)	0.56 ± 0.13	1.2 ± 0.24	2.0 ± 0.35	0.78 ± 0.25
MSH(w/o gating)	0.78 ± 0.15	1.0 ± 0.31	2.2 ± 0.76	0.44 ± 0.22
MSH(w/ gating)	0.76 ± 0.13	0.92 ± 0.22	1.9 ± 0.41	0.45 ± 0.21

Table 1: DTI indices over all acquisition methods

In an equal scan time unit, we discovered a trade-off with SSH and MSH. While MSH shows reduced SSH-related artifacts, the ability to provide robust tractography is mitigated and the overall SNR is lower. We propose that the goal is to generate artifact free DTI so that the individual tracts of the spinal cord can be examined and related to neurological function, but more work is necessary to do this in an acceptable scan time and with high SNR.

References: [1] Hofling et al. NMR Biomed, 2009, [2] Smith *et al.*, NMR Biomed, 2010, [3] Jeong *et al.*, ISMRM 2010, [4] Landman *et al.*, Neuroimage 2007, [5] Jiang *et al.*, Comput Methods Programs Biomed. 2006. **Grant Support**: NIH/NIBIB BRP EB000461, NIH/NIBIB K01 EB009120